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Water Quality Conditions and Trophic Status of Lake Toba, North Sumatra, Indonesia: Implications for Lake Management

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ABSTRACT

Lake Toba, the largest lake in Indonesia and Southeast Asia, is a multifunctional ecosystem supporting fisheries, tourism, transportation, domestic water supply, hydropower generation, agriculture, and surrounding human settlements. This study comprehensively evaluated the spatial and temporal variations in water quality and trophic status using integrated water quality indices and trophic state indicators. Surface water samples were collected from 21 stations during the dry and rainy seasons of 2024. Water quality was assessed using the Pollution Index (PI) and the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI), and trophic status was determined using the Trophic State Index (TSI) and TSIlamp. PI results classified Lake Toba as lightly polluted under Class I criteria (3.53 ± 0.82 dry season; 3.44 ± 0.81 rainy season) and good to lightly polluted under Class II standards (1.72 ± 0.59 dry; 1.74 ± 0.78 rainy season). Trophic conditions ranged from oligotrophic to eutrophic across the stations, with an overall mesotrophic status. The mean trophic index increased from 42.37 ± 3.43 in the dry season to 47.03 ± 3.98 in the rainy season, indicating a gradual increase in ecosystem productivity. Although the overall water quality remains suitable for Class II uses, the upward trophic trend signals increasing nutrient pressure. These findings underscore the need for proactive management, particularly the regulation of floating net-cage aquaculture expansion, to mitigate organic loading and prevent progressive eutrophication in Lake Toba.

Introduction

Lake Toba is the largest lake in Indonesia and Southeast Asia and the world's largest volcanic lake [1,2]. Located in North Sumatra Province, the lake covers a surface area of approximately 1,124 km², with a maximum depth of 508 m and an estimated water volume of 256.2 million m³ [3]. The Toba Caldera was designated as a UNESCO Global Geopark on July 7, 2020, during the UNESCO Executive Council session in Paris, reflecting its outstanding geological value and strong cultural linkages with local communities, particularly in relation to biodiversity and traditional practices [4]. Lake Toba, which extends from north to south in central North Sumatra, constitutes a highly strategic and multifunctional ecosystem. Historically, the lake served as an important fishing ground supporting endemic species such as "*Ihan Batak*" (*Neolissochilus*

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thienemanni); however, its fish community is currently dominated by introduced species, including tilapia and invasive “red devil” cichlids [5]. Over the past decades, floating net cage aquaculture has expanded rapidly, operated by both local communities and national or international enterprises [6]. In addition, Lake Toba functions as a major transportation corridor, with more than 20 ports connecting the surrounding regions; serves as a raw-water source for local communities and the regional drinking-water company (*Tirtanadi*); and supplies water to the Sigura-Gura Hydroelectric Power Plant (HEPP). Furthermore, Lake Toba has emerged as a leading tourist destination and has been designated as a super-priority tourism area in Indonesia [7,8]. These diverse anthropogenic activities inevitably exert increasing pressure on the lake’s ecological condition, particularly its water quality and trophic status.

As the largest lake in Southeast Asia, Lake Toba has attracted considerable scientific attention at the local, national, and international levels. Previous studies have addressed various aspects, including lake morphometry [3], aquatic biota [9,10], tourism, and water-based recreational activities [11,12], and the socio-cultural dynamics of communities surrounding the lake [13,14]. Geological research related to the Toba Caldera Geopark has also been extensively documented [1,15]. Studies focusing on water quality and trophic status have increased in recent decades; however, most studies remain spatially or temporally constrained. For example, assessments of organic pollution load capacity have often relied on single-season sampling during the rainy period [16,17], while evaluations of water quality and trophic status during the transitional or dry seasons have been limited to specific areas, particularly in the northeastern part of the lake [18]. More recent studies examining seasonal trophic dynamics have largely focused on the eastern region of Lake Toba, including eastern Samosir Island and Pangururan City [10,19,20].

However, comprehensive assessments of water quality that integrate both spatial and temporal dimensions are lacking in existing research. This gap is critical because spatial variability in water quality arises from differences in topography, land-use patterns around the lake, and distinct hydrological characteristics within the lake basin. Temporally, fluctuations in rainfall intensity and subsequent rainwater runoff further influence aquatic conditions. Moreover, the multifunctional ecosystem of Lake Toba, which serves as a source of raw water and supports fisheries (capture and aquaculture), tourism, transportation, and water sports, necessitates spatially and temporally comprehensive water quality data to inform sustainable management strategies. This study presents the first comprehensive spatial and temporal analysis of the water quality status and trophic dynamics in Lake Toba. Such data are essential for mitigating pollutant influx from the surrounding areas and preserving the lake’s ecological integrity, thereby ensuring long-term sustainable use.

Materials and Methods

Study Area, Measurement, and Sampling

The study was conducted in August 2024 (dry season) and November 2024 (rainy season) in the Lake Toba Ecosystem. According to a 2024 report from the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG), the climate in the Toba region and its surroundings falls within the Equatorial Monsoon category, with two peak rainfall events. Furthermore, the BMKG report states that the peak dry season in the Toba region and its surroundings occurs in July-August, while the peak rainy season occurs in November–December [21]. A total of 21 observation points (Figure 1) were selected to represent various regions and utilization activities, including floating net cage aquaculture, tourism, residential areas, ferry ports, agriculture, and the lake outlet (Table 1). The measurement and sampling of water followed the American Public Health Association (APHA) standard [22], which includes the physical, chemical, and biological parameters of water (Table 2). The measured water quality refers to surface water (0.5–1 m depth) and therefore does not capture the potential vertical stratification effects, particularly during periods of thermal stability.

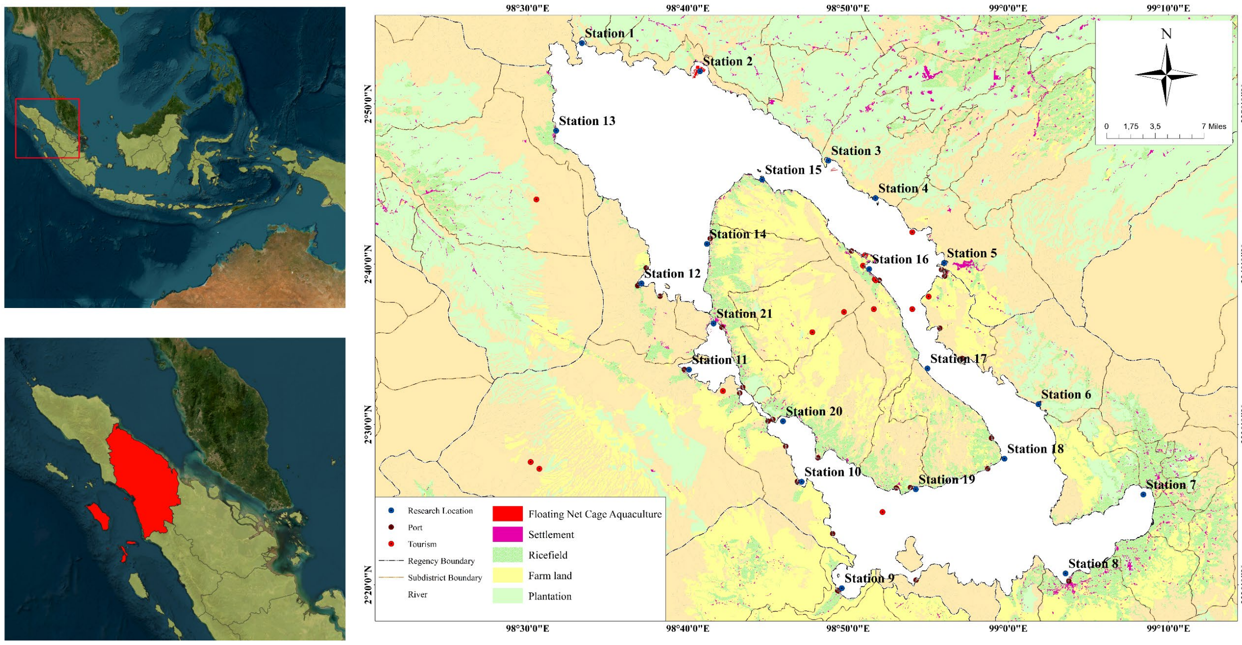

Figure 1. Study area and spatial distribution of 21 sampling stations used for water quality assessment in Lake Toba, North Sumatra, Indonesia. Insets show the regional location of Lake Toba within Indonesia and Sumatra Island. Sampling stations were determined based on aquatic conditions related to water utilization and land use around the water body, which have the potential to contribute to nutrient inputs and reflect the spatial distribution of the Lake Toba area.

Table 1. Spatial distribution of anthropogenic activities and hydrological features potentially affecting water quality at sampling stations in Lake Toba. Twenty-one observation stations in all were chosen to reflect different places and uses, such as tourism, residential neighbourhoods, ferry ports, agricultural, floating net cage aquaculture, and the lake outlet.

No	Activity	Locations	Description
1	Residential areas	Station 1, 2, 5, 8, 9, 10, 11, 13, 21	The cities of Balige (station 8) and Pangururan (station 21) are the capitals of the Samosir and Toba Regencies, respectively. Another densely populated area is Parapat (station 5), which is also a major tourist destination
2	Floating net cage aquaculture	Station 2, 3, 12, 13	Haranggaol (Station 2) and Silalahi (Station 13) are the net cage centers on Lake Toba.
3	Tourism	Station 5, 8, 16, 21	Parapat (Station 5) and Tomok (Station 16) are tourist centers on Lake Toba.
4	Livestock	Station 9 and 13	In every settlement around Lake Toba, there are many pig pens, and the largest one is in Silalahi (station 13)
5	Ferry ports	Station 3, 9, 10, 15, 16, 20	There are at least 10 ferry ports in the Lake Toba area, where Tomok port (station 16), Simanindo (station 15), and Tigaraksa are the largest ports in the Lake Toba area.
6	Agriculture	Station 6, 9, 14, 19	Nearly the entire Lake Toba area is agricultural/plantation, except for Station 4, the Pondok Buluh Educational Forest. However, the largest agricultural area was in the Aek Lintas watershed (Station 9).
7	Fishing activities	1–21	Traditional fishing is carried out in all locations
8	Lake inlet	Station 6 and 8–13	The Aek Silang River (station 9) is the largest river flowing into Lake Toba, with a velocity of 10.61 m/s, compared to other rivers with flows of less than 3 m/s [16]. The Aek Silang microhydro power plant is also located on this river
9	Lake outlet	Station 7	The only outlet of Lake Toba that flows into the Asahan River

Table 2. Water quality parameters, analytical methods, units, sampling approach, and applicable water quality standards used in this study. The maximum permissible limits for specific physical, chemical, and microbiological characteristics for Class I and Class II surface water are shown in this table in accordance with water quality standards in Indonesia and WHO. The metrics, which are frequently used to evaluate lake water quality and adherence to environmental rules, include markers of organic pollutants, nutrients, and microbiological contamination.

Parameters	Instruments/methods	Units	Description	Water quality standards		
				Class I*	Class II*	WHO**
Temperature	DO meter/ Lutron DO-5510	^0C	In-site	Dev 3	Dev 3	-
Transparency	Secci disch	m	In-site	10	4	-
Turbidity	Turbidity meter	NTU	In-site	-	-	5
TDS/Total Dissolved Solid	HACH, HQ40D	mg/L	Ex site	1,000	1,000	1,000
TSS/ Total Suspended Solids	HACH, HQ40D	mg/L	Ex site	25	50	-
Oil and grease		mg/L	Ex site	1	1	-
Current	Satellite imagery/Aqua Modis	m/s	Ex site	-	-	-
pH	pH meter (Atago DPH-2)	-	In-site	6-9	6-9	6.5-8.5
DO/ Dissolved Oxygen	DO meter/ Lutron DO-5510	^0C	In-site	6	4	5
COD/ Chemical Oxygen Demand	Incubation and winkler	mg/L	Ex situ	10	25	10
BOD/ Biological Oxygen Demand	Reflux method	mg/L	Ex situ	2	3	5
NO_3^-/Nitrate	Spectrophotometer (UV-Vis Shimadzu 1240)	mg/L	Ex situ	-	-	50
NO_2^-/Nitrite	Spectrophotometer (UV-Vis Shimadzu 1240		Ex situ	-	-	3
NH_3^-/Ammonia	Spectrophotometer (UV-Vis Shimadzu 1240		Ex situ	-	-	-
Total Nitrogen/TN	Spectrophotometer (UV-Vis Shimadzu 1240		Ex situ	0.65	0.75	-
PO_4^-/Phosphate	Spectrophotometer (UV-Vis Shimadzu 1240)	mg/L	Ex situ	0.01	0.03	-
Fecal coliform	MPN (*Most Probable Number*): Presumptive test and Confirmed test	MPN/ 100mL	Ex situ	100	1000	0
Chlorophyl-a	Filtration method	mg/m^3	Ex situ	10	50	-
	Satellite imagery/Aqua Modis	mg/m^3	Ex situ	10	50	-

Note : Water quality standards in *Indonesia [23]; **WHO [24]

Data Analysis

This study primarily employed descriptive statistics and index-based assessments to characterize the spatial–temporal patterns in Lake Toba. Given that sampling was conducted during two contrasting seasons (dry and rainy) within a single year, these seasonal observations did not constitute independent temporal replicates. Therefore, formal inferential tests such as ANOVA were not applied, as the study aimed to evaluate seasonal contrasts rather than test statistically independent temporal hypotheses. This approach enabled the identification of key interactions and potential controlling factors influencing water quality dynamics and trophic responses.

Owing to the large number of observation points (21 observation stations) in this study, we will attempt to divide it into eight regions based on the four cardinal directions on Samosir Island and the four cardinal directions on Sumatra Island (mainland) in the future, in addition to describing each location. This is especially important because the CCME index requires repeated measurements at the same location.

The Pollution Index (PI)

The Pollution Index (PI) method is determined for a single designation and then applied to multiple designations across all or part of a waterbody. This method is determined by selecting parameters that indicate good water quality, if they have a low value [25,26]. The classification of Water Quality based on the PI Method is 0–1 (good); 2–5 (lightly polluted); 6–10 (moderately polluted); and >10 (heavily polluted) [25,26]. Equation 1 presents the calculation of the pollution index, as follows:

$$\mathrm{PI} = \sqrt[2]{\frac{\left(\frac{Ci}{Li}\right)^2 \text{maximum} + \left(\frac{Ci}{Li}\right)^2 \text{average}}{2}} \quad (1)$$

Description:
PI = Pollution Index, which is a function of Ci/Li
Li = quality standard value
Ci = measured concentration of water quality parameter (i)

The Canadian Council of Ministers of the Environment (CCME)

The Canadian Council of Ministers of the Environment (CCME) assesses water quality by comparing data against established thresholds. This method was formulated by the British Columbia Ministry of Environment, Lands, and Parks and later developed by Alberta Environment. The CCME has been implemented in Canada and various other countries to assess sediment, drinking water, and agricultural water quality [27–29]. The CCME is a globally recognised water quality index [28] and is therefore used to assess the water quality of Lake Toba alongside the indices used in Indonesia. Equation 2 presents the calculation of the CCME, as follows:

$$\mathrm{CCME} = 100 - \left[\frac{\sqrt{F1^2+F2^2+F3^2}}{1.732}\right] \quad (2)$$

Description:
F1 = Total number of parameters exceeding guideline limits
F2 = The frequency of test results exceeding water quality guidelines
F3 = The amplitude of deviation from water quality guidelines
1.732 = normality value 0–100

The classification of Water Quality based on the CCME Method is: 95–100 (Excellent); 80–94 (Good); 65–79 (Fair); 45–64 (Marginal); and 0–44 (Poor) [27].

Trophic Status Index (TSI)

The trophic status of a water body reflects the magnitude of nutrient inputs and overall ecosystem productivity. Several key parameters closely related to nutrient enrichment can be used to evaluate trophic conditions. The Trophic State Index (TSI) was originally developed by Carlson (1977) using three indicators of lake fertility: chlorophyll a concentration, total phosphorus, and water transparency (Secchi disc depth). Equation 6 presents the calculation of the Trophic Status Index (TSI), as follows [30]:

$$\mathrm{TSI}_{\text{chlorophyll}} = 9.81 \ln \text{chlorophyll} - \text{a concentration } (\mu g/l) + 30.6 \quad (3)$$

$$\mathrm{TSI}_{\text{transparency}} = 60 - 14.41 \mathrm{In} \text{ Secchi disk depth (m)} \quad (4)$$

$$\mathrm{TSI}_{\text{phosphorus}} = 14.42 \ln \text{total phosphorus concentration } (\mu g / L) + 4.15 \quad (5)$$

$$\mathrm{TSI} = \frac{\mathrm{TSI}_{\text{chlorophyll}} + \mathrm{TSI}_{\text{transparency}} + \mathrm{TSI}_{\text{phosphorus}}}{3} \quad (6)$$

Water fertility was classified into the following categories: <30 (oligotrophic), 30–40 (hypolimnetic), 40–50 (mesotrophic), 50–70 (eutrophic), and >70 (hypertrophic).

Trophic State Index Lamp (TSI_{lamp})

The Trophic State Index for tropical aquatic systems was later updated by Bucci et al. [31] to create the TSIlamp, which relies solely on the concentration of chlorophyll-a and total phosphorus. Because tropical waters frequently have different environmental conditions than temperate lakes, this simplified index was created to more accurately depict trophic dynamics in tropical waters. The TSILamp is a trophic status index for tropical waters, based on only two parameters: chlorophyll and total phosphate. Equation 9 presents the calculation of the TSI Lamp, as follows [31]:

$$\mathrm{TSI}_{\text{chlorophyll}} = 10 \times \left(6 - \left[\frac{0.92 - 0.34 \mathrm{xln} \text{ chlorophyll} - \mathrm{a}}{\ln 2}\right]\right) \quad (7)$$

$$\mathrm{TSI}_{\mathrm{TP}} = 10 \times \left(6 - \left[\frac{1.77 - 0.42 \mathrm{xln} \text{ TP}}{\ln 2}\right]\right) \quad (8)$$

$$\mathrm{TSI}_{\text{lamp}} = \frac{TSI_{chlorophyll-a} + TSI_{TP}}{2} \quad (9)$$

The trophic status categories for aquatic environments are as follows: TSI ≤ 47 (Ultraoligotrophic), 47 < TSI ≤ 52 (Oligotrophic), 52 < TSI ≤ 59 (Mesotrophic), 59 < TSI ≤ 63 (Eutrophic), 63 < TSI ≤ 67 (Super eutrophic), and TSI > 67 (Hypereutrophic).

Results and Discussion

Results

Water Quality Characteristics

The surface water temperature and pH in Lake Toba exhibited relatively low spatial and temporal variability (standard deviations: temperature, 0.70–0.76; pH, 0.46–0.51), reflecting the strong thermal inertia and buffering capacity that are typical of large, deep tropical lakes (Table 3). Surface water temperatures ranged from 24.80 °C to 28.20 °C and showed no pronounced seasonal variation. Slightly higher temperatures were observed during the dry season (25.50–28.20 °C), whereas slightly lower values were observed during the rainy season (24.80–27.80 °C), likely because of increased cloud cover and rainfall-induced mixing. Similarly, pH values ranged from 7.30 to 9.40 and tended to decrease slightly during the rainy season, which was attributable to dilution by precipitation and inflow of river water with a lower pH.

Both spatially and temporally, the nutrient levels in Lake Toba were highly stable, with a standard deviation of <0.10, indicating that nitrogen and phosphorus concentrations were evenly distributed across the surface waters. The concentration of organic matter in Lake Toba is relatively low, with the highest BOD and COD concentrations being recorded at Station 9, with values of 5.80 and 18.40 mg/L, respectively. Station 9 encompasses residential areas, floating net cages, and agricultural land. The organic input at Station 9 were primarily influenced by river discharge. The river at this station, Aek Silang 2, is one of the largest flowing into Lake Toba and is the site of the Aek Silang 2 Baktiraja hydropower plant [7].

Table 3. Summary statistics of water quality parameters in Lake Toba during the dry and wet seasons (N= 21 stations). The detection limit for nitrate (NO_3^-) was 0.40 mg/L; values reported as <0.40 mg/L indicate concentrations below the analytical detection threshold.

Parameters	Unit	Dry season				Wet season			
		Min	Max	Average	stdev	Minimum	Maximum	Average	stdev
Temperature	^oC	25.50	28.20	26.65	0.76	24.80	27.80	26.17	0.71
Transparency	m	1.50	7.00	4.60	1.44	2.50	7.00	4.63	1.38
Turbidity	NTU	0.20	34.62	5.19	8.65	0.11	34.03	4.25	7.30
TDS	mg/L	68.00	81.00	72.40	4.48	66.60	92.00	77.29	7.16
TSS	mg/L	1.00	12.00	3.33	2.77	1.00	1.00	1.00	-
DO	mg/L	7.05	9.80	8.11	0.78	4.40	7.80	6.09	0.89
pH	-	7.30	9.40	8.63	0.46	7.30	8.90	8.25	0.51
BOD	mg/L	1.60	5.80	3.12	0.88	1.10	3.70	2.05	0.79
COD	mg/L	7.00	18.40	10.97	2.82	4.00	11.80	5.84	1.92
NO_3^-	mg/L	<0.40*	0.80	-	-	<0.40*	<0.40*	-	-
NO_2^-	mg/L	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.00
NH_3^-	mg/L	0.01	0.15	0.05	0.05	0.01	0.06	0.02	0.01
Total Nitrogen	mg/L	0.42	0.83	0.47	0.09	0.41	0.46	0.42	0.01
PO_4^-	mg/L	0.03	0.12	0.06	0.03	0.03	0.15	0.07	0.03
Oil & grease	mg/L	0.54	1.40	0.82	0.23	0.10	0.62	0.30	0.12
Fecal coliform	MPN/100mL	2.00	2,800.00	217.62	616.07	20.00	260.00	64.80	72.93
Chlorophyll-a	mg/m^3	0.19	2.01	0.78	0.45	1.24	4.23	2.72	0.74

Land-use around Station 9 mainly comprises agricultural areas originating from Humbang Hasundutan. The lowest organic matter concentrations were observed at Station 12, with BOD concentration being recorded as 1.60 mg/L during the dry season and only 1.10 mg/L during the rainy season. The COD concentrations were 7.80 mg/L in the dry season and 4 mg/L in the rainy season. The low organic matter levels at this station were likely due to minimal organic input from external sources and within the lake itself. Land-use in this area remains relatively natural, with only a small river flowing into the lake. No floating net cages were found in this location. Dissolved oxygen decreased from 8.11 ± 0.78 mg/L in the dry season to 6.09±0.89 mg/L in the rainy season, suggesting an increased biological oxygen demand associated with elevated phytoplankton biomass.

Nutrient concentrations (nitrate and phosphate) in the surface waters of Lake Toba were low, with the highest total nitrogen (TN) concentration during the dry season being recorded at Station 8 (0.8308 mg/L), whereas, in the rainy season, the highest concentration was observed at Station 2 (0.4597 mg/L). The elevated TN levels at Station 2 were attributed to the discharge of uneaten fish into lake water, as Station 2 is a high-density floating net cages area. The elevated TN levels at Station 21 were likely due to its proximity to Pangururan, as the domestic activities in this area contributed to the discharge of organic matter and nutrients into the water. Total nitrogen showed relatively minor seasonal variation (0.47 vs 0.42 mg L^{-1}), indicating that spatial heterogeneity rather than seasonal fluctuation dominates nutrient distribution patterns.

Furthermore, contamination by *Fecal coliform* bacteria has become a serious issue in many countries [32]. The measured fecal coliform levels in Lake Toba ranged from 1.80 to 2800 MPN/100 mL. *Fecal coliform* are dynamic bacteria that fluctuate between the dry and rainy seasons (stdev, 50). During the dry season, the highest *Fecal coliform* concentration was recorded at Station 13, reaching 2800 MPN/100 mL, whereas the lowest levels (<1.40 MPN/100 mL) were observed at Stations 4 and 5. The elevated fecal coliform levels at Station 13 were suspected to originate from large mammal excrements, particularly pig and dog waste, which are commonly found in this area. Coliform bacteria are an indicator of environmental contamination and poor sanitation; therefore, the presence of fecal coliform is used as a pollution indicator because their colony count is positively correlated with the presence of pathogenic bacteria [32].

The in-situ measurements of chlorophyll-a concentration in Lake Toba during the dry season ranged from 0.1868 to 2.0069 mg/m³, with an average of 0.77 mg/m³. During the rainy season, in-situ measurements indicated a chlorophyll-a concentration range of 1.24–4.23 mg/m³, with an average of 2.72 mg/m³. Meanwhile, chlorophyll-a concentrations extracted from satellite imagery in August 2024 (dry season) ranged from 0.65 to 10.45 mg/m³, with an average of 1.83 mg/m³. In the rainy season, satellite-derived chlorophyll-a concentrations ranged from 1.72 to 60.11 mg/m³, with an average of 9.77 mg/m³. Thus, Lake Toba is oligotrophic during the dry season and mesotrophic during the rainy season. This increase was driven by elevated nutrient input, particularly phosphate and nitrogen, from rainwater runoff, which stimulated rapid phytoplankton growth [33]. These changes are common in water bodies and are affected by increased anthropogenic inputs [16]. Chlorophyll-a concentrations in aquatic environments are influenced by nutrients such as nitrate, phosphate, and silicate [34], with nitrate being the primary factor affecting its levels. Higher nitrate concentrations in the water corresponded to increased chlorophyll-a levels. The substantially higher satellite-derived chlorophyll-a values (up to 60 mg/m³ during the rainy season) compared to in-situ measurements likely reflect optical interference from suspended particles, coloured dissolved organic matter (CDOM), and cloud contamination effects, particularly during high-runoff periods. Remote sensing algorithms developed for optically complex tropical waters may overestimate chlorophyll concentrations under high turbidity conditions. Therefore, satellite data should be interpreted cautiously and validated using concurrent in-situ measurements.

Spatially (Figures 2 and 3), the highest chlorophyll-a concentration was recorded at Station 9, reaching 2.01 mg/m³. This is attributed to the presence of rice fields, residential areas, plantations, and an inlet river flowing into Lake Toba at this station. Organic matter and nutrient concentrations were also relatively high at Station 9. Temporally, chlorophyll-a levels in Lake Toba increased during the rainy season, as its concentration was influenced by seasonal variations, with higher levels observed during the rainy season owing to direct runoff carrying nutrients from terrestrial sources into the lake [33,35]. For instance, the chlorophyll-a concentration at Station 20 increased considerable from 0.844 to 4.229 mg/L during the dry and rainy seasons, respectively. This increase was driven by elevated nutrient input, particularly phosphate and nitrogen, from rainwater runoff, which stimulated rapid phytoplankton growth [33]. These changes are common in water bodies and are affected by increased anthropogenic inputs [16]

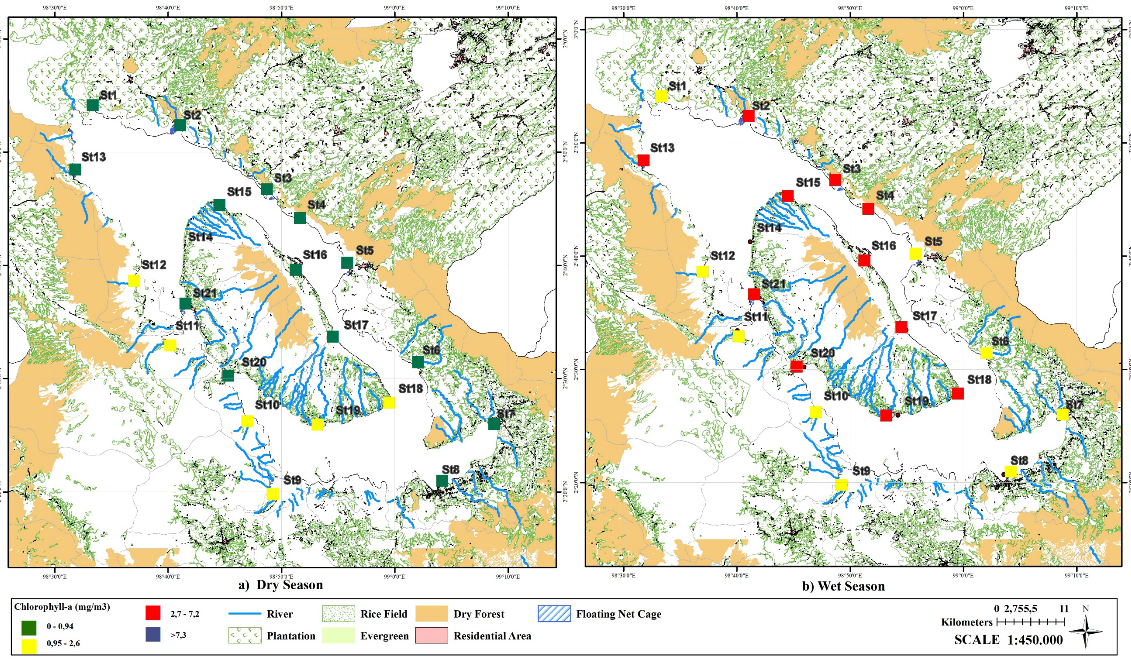

Figure 2. Spatial distribution of in-situ chlorophyll-a concentrations (mg/m³) in Lake Toba during the dry (a) and rainy (b) seasons. This figure presents the spatial distribution of chlorophyll a concentration (mg/m³) across sampling stations (St1–St21) during the dry season (a) and wet season (b). Colour-coded markers indicate chlorophyll a concentration ranges, highlighting spatial variability between seasons. Overall, the figure shows a clear seasonal shift, with generally higher and more widespread elevated chlorophyll a concentration during the wet season, suggesting increased nutrient input and primary productivity linked to hydrological changes

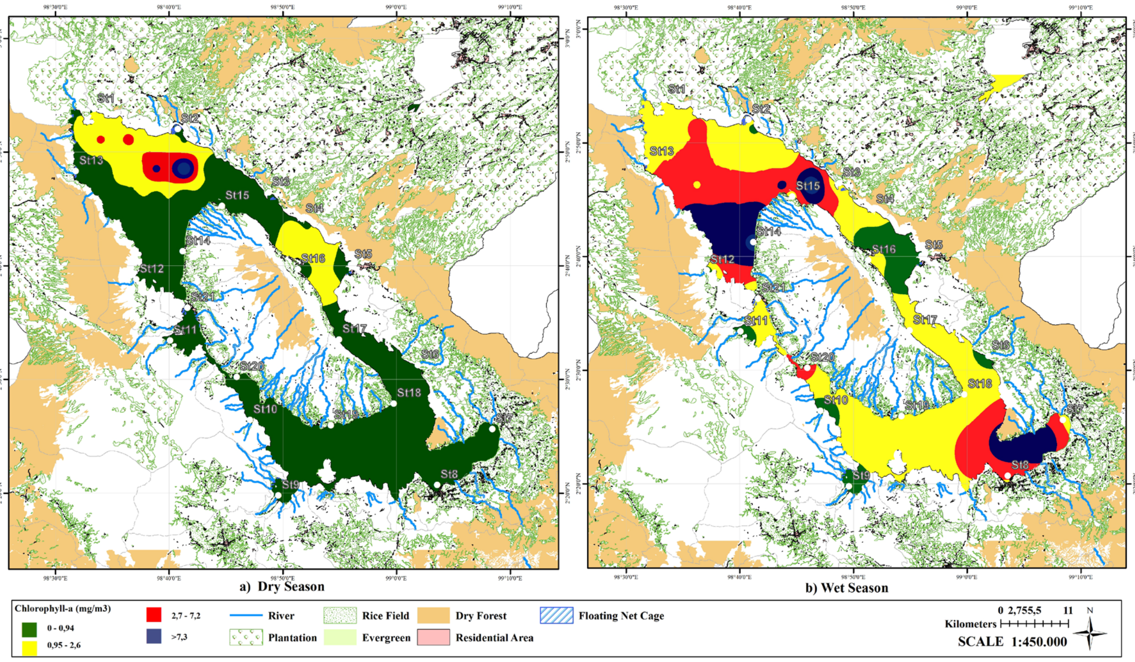

Figure 3. Spatial distribution of satellite-derived chlorophyll a concentration (mg/m³) in Lake Toba during the dry (a) and rainy (b) seasons. This figure illustrates the interpolated spatial distribution of chlorophyll-a concentrations (mg/m³) across the study area for the dry season (a) and wet season (b), based on measurements from sampling stations (St1–St21). Color gradients represent concentration ranges, revealing localised hotspots and broader spatial trends. The results indicate a marked seasonal contrast, with relatively low and homogeneous chlorophyll-a levels during the dry season, while the wet season exhibits higher concentrations and expanded high-productivity zones, particularly in central and downstream areas, likely driven by increased runoff and nutrient loading.

The quantitative analysis of correlation strength indicated that several strong relationships (|r| > 0.5) characterized the water quality dynamics of Lake Toba (Figure 4). During the dry season, strong positive correlations between BOD and COD (r > 0.7) and negative associations between DO and organic parameters (r < −0.5) suggest that internal organic matter decomposition is the dominant control. In contrast, the rainy season showed stronger correlations between phosphate and chlorophyll-a (r > 0.5) (Figure 4), indicating enhanced phosphorus-driven productivity under runoff conditions. These seasonal variations show that during low-flow times, internally controlled processes give way to externally induced nutrient enrichment during the rainy season. A change in the primary drivers of water quality was found through seasonal assessments of correlation patterns. Strong positive correlations between BOD and COD and negative correlations with dissolved oxygen indicate that organic matter dynamics were more prevalent during the dry season. Phosphate and chlorophyll-a, on the other hand, showed greater correlations during the wet season, suggesting increased phosphorus-driven productivity under runoff conditions. During the rainy season, turbidity and suspended particles had higher nutritional connections, indicating the importance of external loading during this time. These results imply that whereas external nutrient inputs, especially phosphorus, exert more control during the rainy season, internal biogeochemical processes predominate under low-flow circumstances.

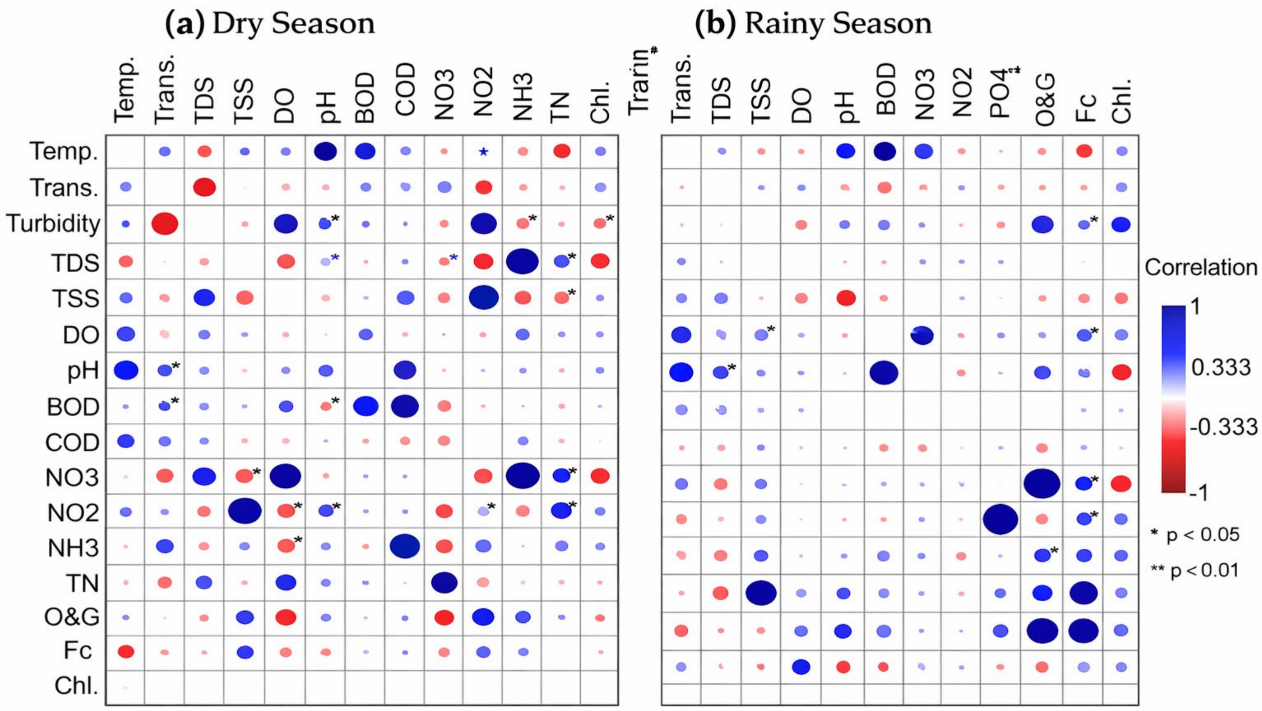

Figure 4. Seasonal comparison of Pearson correlation coefficients among water quality parameters in Lake Toba during the dry (a) and rainy (b) seasons. Circle size and color represent the strength and direction of correlations (blue = positive, red = negative), while asterisks indicate statistically significant relationships (* $p < 0.05$; ** $p < 0.01$). The matrices highlight seasonal differences in parameter interactions, with the rainy season showing stronger and more numerous correlations, particularly among nutrients and chlorophyll-a.

Lake Pollution Status

The Pollution Index (PI) results indicated that Lake Toba was classified as lightly polluted under Class I criteria, with mean values of 3.53 ± 0.82 during the dry season and 3.44 ± 0.81 during the rainy season. Under Class II standards, the lake ranged from good to lightly polluted conditions, with mean PI values of 1.72 ± 0.59 (dry season) and 1.74 ± 0.78 (rainy season) (Figure 5). Similarly, the CCME-WQI assessment categorized Lake Toba as good to lightly polluted under Class I criteria, with mean index values of 64.47 ± 4.80 in the dry season and 69.28 ± 4.47 in the rainy season (Figure 5). Under Class II standards, water quality is classified as good to very good, with mean values increasing from 79.50 ± 6.22 (dry season) to 85.35 ± 4.87 (rainy season) (Figure 6). These results demonstrate generally stable seasonal conditions, with slightly improved CCME-WQI scores during the rainy season, likely reflecting the dilution effects. Taken together, these results demonstrate that

Lake Toba is generally suitable for Class II purposes, including tourism, fisheries, and agriculture. However, additional management measures are required to ensure consistent compliance with Class I standards, particularly for drinking water supply.

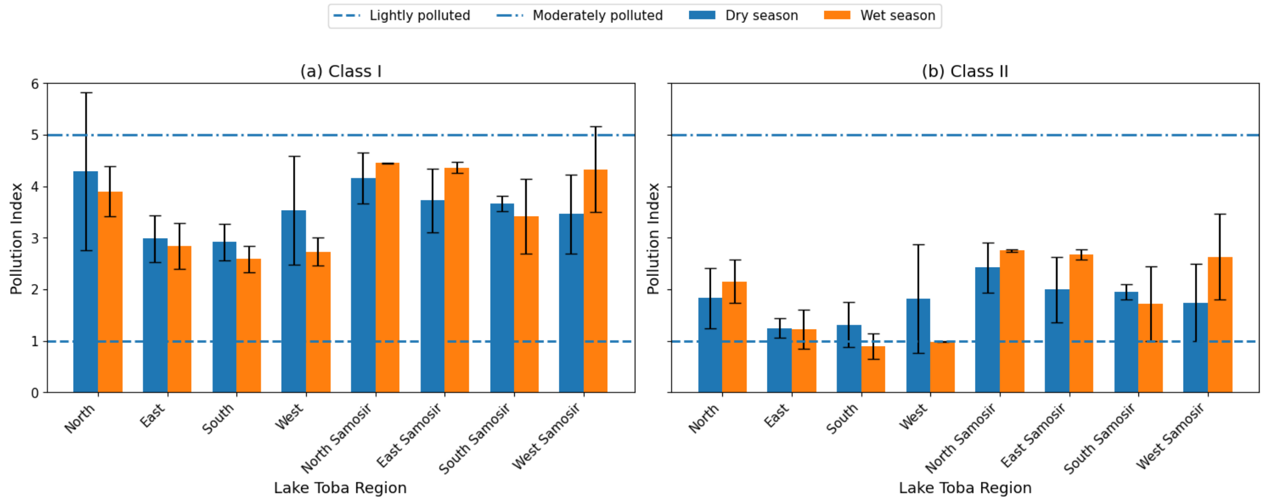

Figure 5. Spatial variation in the pollution index (mean ± standard deviation) of Lake Toba during the dry and wet seasons based on (a) Class I and (b) Class II water quality standards. The horizontal dashed and dash–dot lines indicate the thresholds for lightly polluted (PI = 1) and moderately polluted (PI = 5) conditions, respectively.

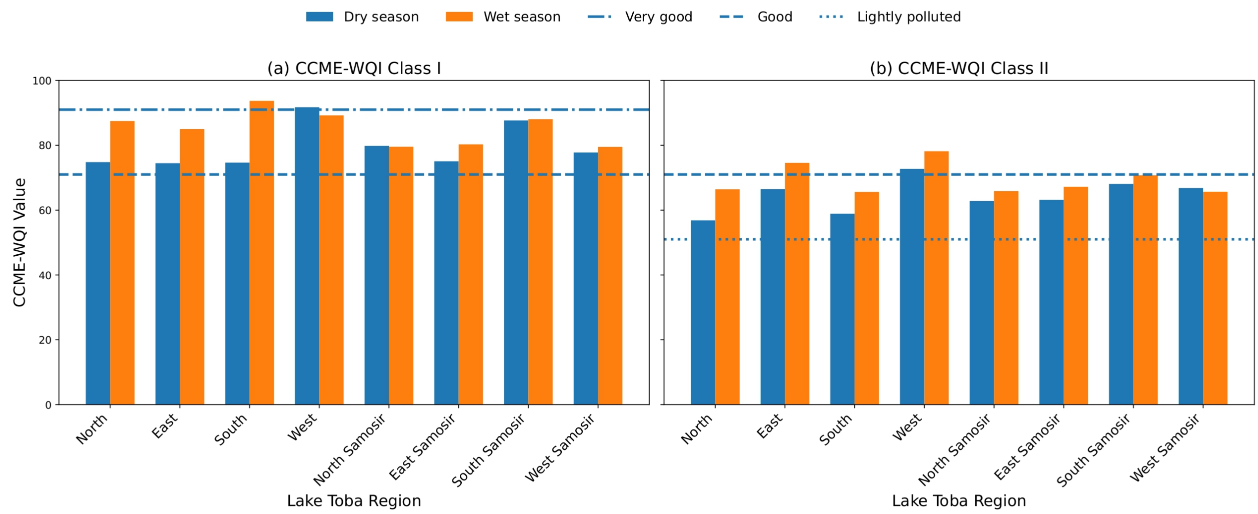

Figure 6. Spatial variation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) in Lake Toba during the dry and wet seasons based on (a) Class I and (b) Class II water quality standards. Horizontal lines indicate the CCME-WQI classification thresholds for very good, good, and lightly polluted water quality.

Spatially, the northern region and area surrounding Samosir Island were more polluted than the other lake regions (Figures 7 and 8). The northern part of Lake Toba contains large-scale floating net cages at Haranggaol (Station 2) and Silalahi-Paropo (Station 13), which are expected to contribute to aquaculture waste pollution. However, the nutrient concentrations in these areas were relatively low. Instead, the primary suspected source of pollution in the northern region, particularly at Station 13, was fecal coliform contamination originating from livestock waste. Meanwhile, the area surrounding Samosir Island (Stations 14–21) comprised residential and agricultural zones, leading to a higher pollution load from these activities. Additionally, the shallower waters surrounding Samosir Island (Stations 14–21) likely experienced frequent mixing, ensuring the continuous availability of nutrients over time. Furthermore, sufficient light availability in the northern region, owing to the low canopy cover, may have stimulated microbial activity, thereby accelerating the degradation of organic matter into nutrients. Consequently, the chlorophyll concentrations at Stations 14–21 were higher than those at other locations.

Temporally, the water quality in Lake Toba was better during the rainy season than during the dry season. This improvement was attributed to high rainfall, which diluted the pollutant concentrations in the water. Conversely, during the dry season, pollutants become more concentrated, leading to elevated concentrations of contaminants, particularly organic matter, COD, and BOD.

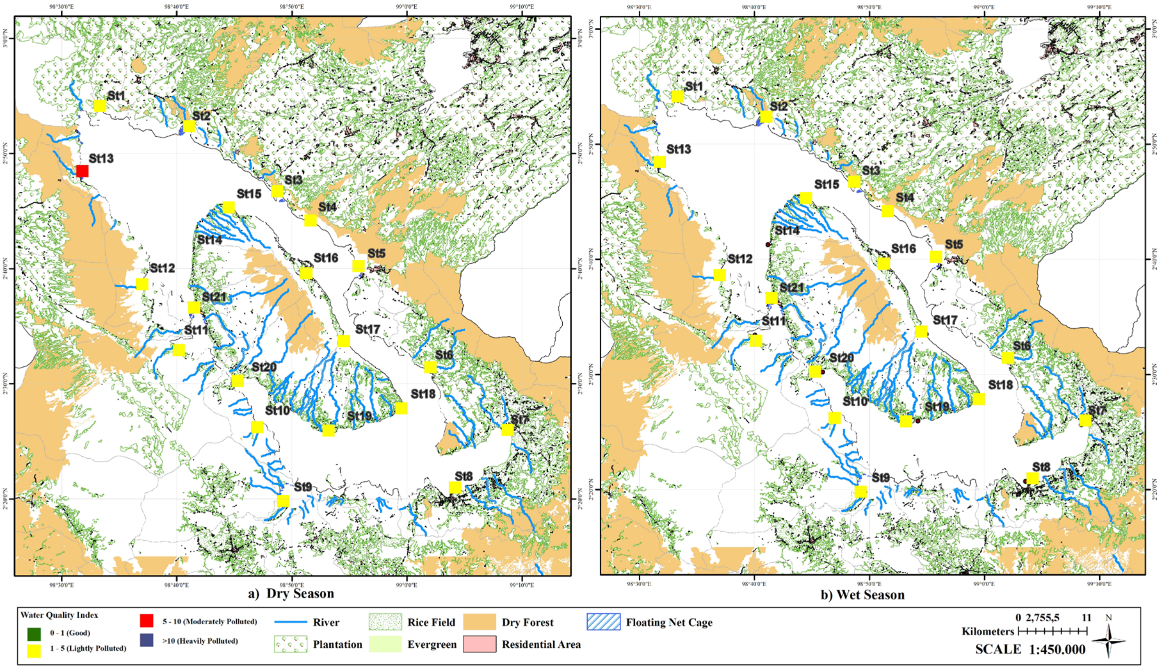

Figure 7. Spatial distribution map of water quality status in Lake Toba during the dry season (a) and rainy season (b) for Class I. The maps incorporate surrounding environmental features such as river networks, land use types, and floating net cage areas to provide spatial context. Color-coded symbols classify water quality status into categories ranging from good to heavily polluted.

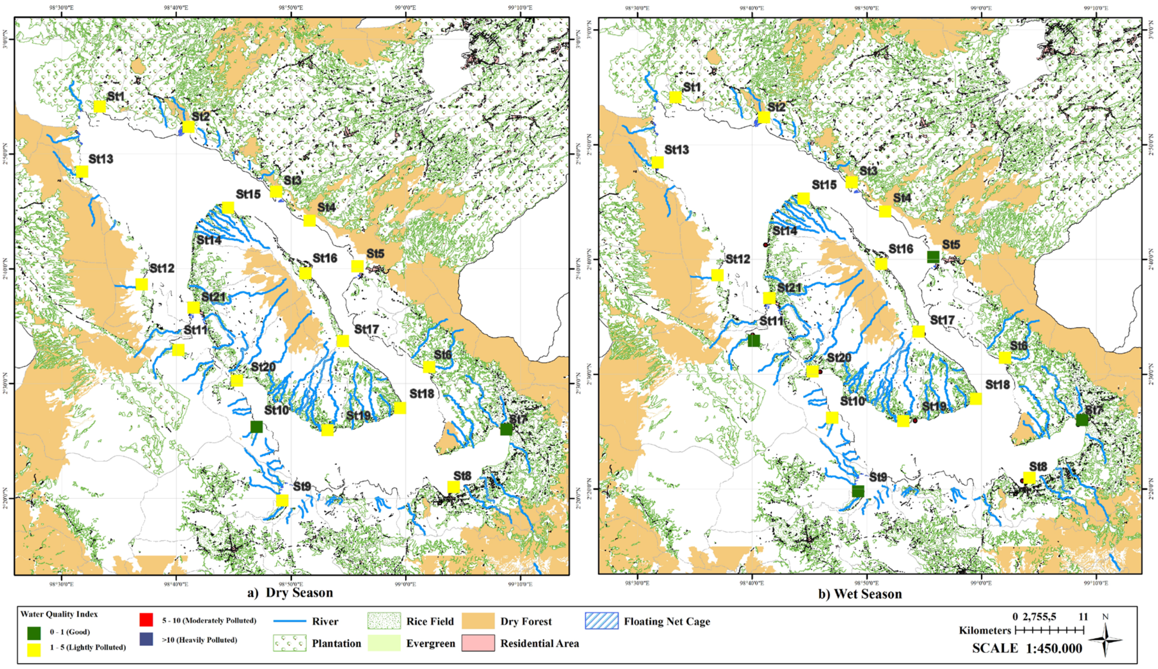

Figure 8. Spatial distribution map of water quality status in Lake Toba during the dry season (a) and rainy season (b) for Class II. The maps incorporate surrounding environmental features such as river networks, land use types, and floating net cage areas to provide spatial context. Color-coded symbols classify water quality status into categories ranging from good to heavily polluted.

Temporally, the water quality conditions in Lake Toba were generally better during the rainy season than during the dry season (Figures 7 and 8). This seasonal improvement is primarily attributed to the dilution effects associated with increased rainfall and river inflow. Conversely, during the dry season, reduced hydrological flushing results in higher pollutant concentrations, leading to elevated levels of organic matter, COD, and BOD in the water.

The overall condition of Lake Toba is comparable to that of other large lakes in Indonesia (Table 4). For example, Lake Maninjau (West Sumatra) has been reported to range from good to moderately polluted under Class I criteria and from lightly to moderately polluted under Class II criteria [36], although more recent studies indicate a deterioration toward severe pollution [37]. Lake Poso (South Sulawesi) remains classified as good to slightly polluted [38,39], while Lake Singkarak (West Sumatra) is categorised as moderately polluted under Class II criteria [40]. Rawa Pening Lake (Central Java) is generally classified as slightly polluted [41], and Lake Sentani (Papua) ranges from slightly to moderately polluted [42]. These comparisons suggest that large, priority lakes in Indonesia are commonly characterised by slight pollution, whereas smaller lakes in North Sumatra and Aceh tend to experience moderate to severe pollution [35,43,44].

Trophic Status of the Lake

The trophic status of Lake Toba ranged from oligotrophic to eutrophic across the sampling stations, with the overall mean indicating a mesotrophic state (Figure 9). The average trophic index value increased from 42.37 ± 3.43 during the dry season to 47.03 ± 3.98 during the rainy season. Spatially, all locations near Samosir Island exhibited higher productivity than the other areas due to the shallower depth of this area [3,44]. Additionally, the concentration of residential settlements on Samosir Island has contributed to increased nutrient input into the waters. Furthermore, the availability of sufficient light in shallow waters enables phytoplankton to achieve optimal photosynthesis throughout the day. This was also reflected in the higher chlorophyll content around Samosir Island (Table 2), a pattern similar to that observed by Fukushima et al. [44]. Notably, in the northern lake regions, despite the presence of floating net cages in Haranggaol (Station 2) and Silalahi-Paropo (Station 13), the trophic levels remained low, particularly during the dry season. This was further supported by the low chlorophyll values, which are consistent with previous studies indicating that chlorophyll concentrations in this region remained relatively low [44].

Temporally, the productivity of Lake Toba was higher during the rainy season than the dry season (Figure 10). This was indicated by the higher chlorophyll concentrations observed during the rainy season than during the dry season (Figures 2 and 3). This was strongly suspected to be influenced by runoff from land, which transported nutrients into the lake waters. A similar finding was reported by Hastuti et al. [19] who observed that the trophic status of Lake Toba was higher during the rainy season than during the dry season.

Several studies indicated that the overall trophic status of Lake Toba ranges from oligotrophic to eutrophic [16]. Meanwhile, the trophic status of its eastern regions was classified as mesotrophic [18,45], whereas in 2009, it was categorized as oligotrophic [46]. This finding is further supported by the 2017 decree of the Governor of North Sumatra, which classified Lake Toba as eutrophic [47,48]. In the eastern part of Samosir Island, the waters range from mesotrophic to eutrophic [10].

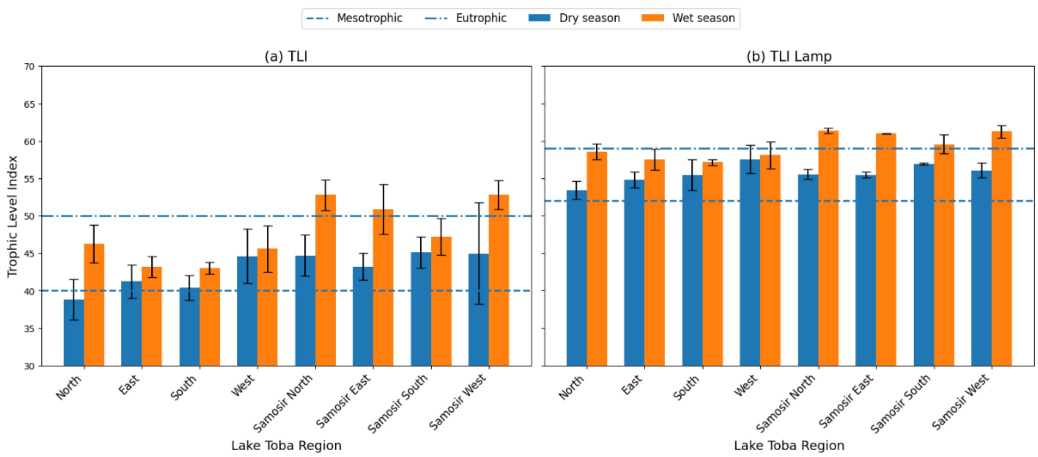

Figure 9. Spatial variation in the trophic state indices of Lake Toba during the dry and wet seasons: (a) Trophic Level Index (TLI) and (b) TLI Lamp. Both panels share the same y-axis scale to allow for direct comparison. Horizontal dashed and dash–dot lines indicate mesotrophic and eutrophic threshold values, respectively.

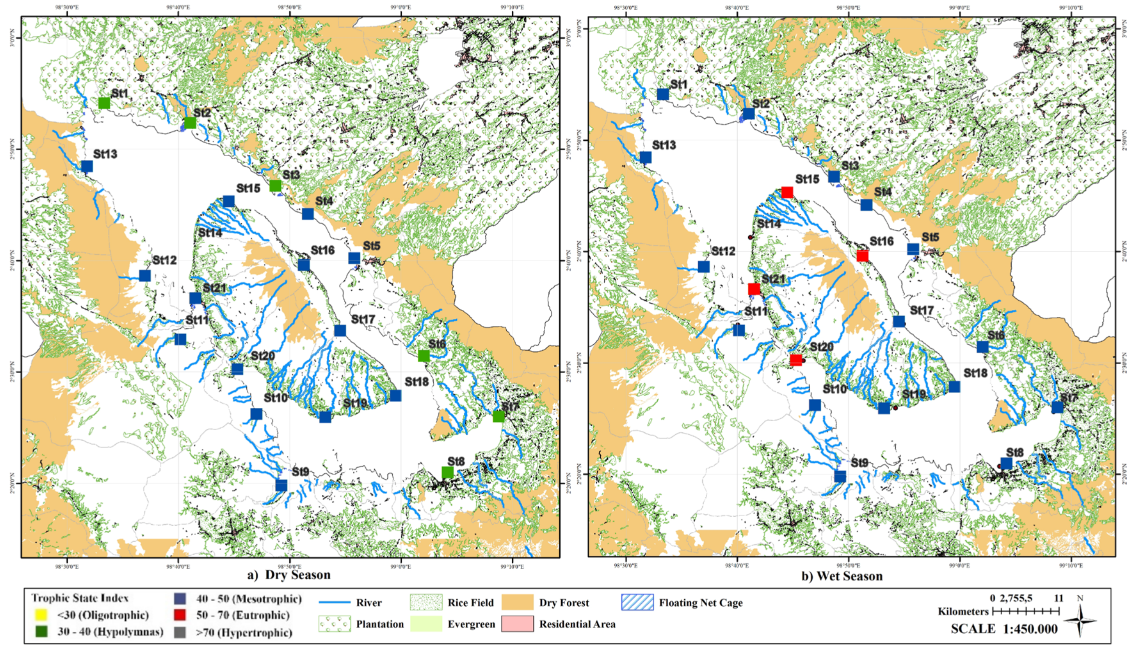

Figure 10. Distribution Map of Lake Toba's Trophic Status During (a) Dry Season and (b) Rainy Season. The maps incorporate surrounding environmental features such as river networks, land use types, and floating net cage areas to provide spatial context. Color-coded symbols classify trophic status into categories ranging from oligotrophic to hypertrophic.

Discussion

Spatial and Temporal Variability of Water Quality

The spatial and temporal dynamics of water quality in Lake Toba are influenced by various factors, including the influence of land use around the catchment [49–51], anthropogenic activities in the lake boundaries [52], lake morphometry [53,54], and seasonal rainfall dynamics [55,56]. Spatially, this is consistent in the northern part and around Samosir Island, where water quality is locally degraded compared to the central part. These areas correspond to zones of intensive land use, including settlements, agriculture, livestock farming, tourism facilities, a ferry port, and fish farming in floating net cages, which collectively increase the input of organic matter and microbial contaminants through surface runoff and direct discharge into the lake boundaries [49–52].

Lake morphometry, particularly related to the shallow lake depth, further exacerbates the impact of anthropogenic pressures on lake water quality. The shallow waters around Samosir Island encourage more frequent vertical mixing and longer pollutant residence times in the surface layer, thus amplifying the effects of local inputs, as reflected in the PI and CCME-WQI results. In contrast, the deeper central basin of Lake Toba, characterised by greater depth and larger water volume, exhibits stronger hydrodynamic dilution and buffering capacity, resulting in lower PI values and higher CCME-WQI scores, indicating relatively better water quality conditions [57,58].

Temporally, lake water quality is strongly influenced by rainfall. During the rainy season, increased rainfall increases surface runoff from the catchment area, transporting nutrients, organic matter, and microbial contaminants from agricultural lands, residential areas, and livestock facilities into the lake. This process contributes to episodic increases in PI values and local decreases in CCME-WQI scores at nearshore stations, particularly those affected by river flow. Simultaneously, higher rainfall and increased river discharge increase lake water volume and flushing rates, driving pollutant dilution in the surface layer [55,56]. Conversely, during the dry season, low rainfall limits surface runoff, reducing nutrient loads. Under these conditions, pollutants originating from nearby sources such as floating net cage aquaculture, domestic wastewater discharge, and port activities tend to accumulate in surface waters [57,58].

Overall, water quality in Lake Toba is controlled by the dynamic interaction between spatially heterogeneous anthropogenic pressures and temporally varying hydrological processes. Because sampling was limited to surface waters, potential hypolimnetic nutrient accumulation and internal loading processes could not be quantified directly. Future studies incorporating vertical profiling are necessary to assess the internal nutrient dynamics better.

Trophic Status Dynamics and Early Eutrophication Signals

The current trophic status of Lake Toba ranges from oligotrophic to eutrophic, with an average in the mesotrophic category, which has increased since 2009 (Table 4), and remains largely oligotrophic [46]. Current findings indicate a gradual shift toward higher trophic levels [10,18]. While this mesotrophic status does not yet indicate severe eutrophication, it serves as an early warning signal of increased nutrient levels that could potentially lead to eutrophication in Lake Toba [59,60]. Higher trophic levels around Samosir Island are closely associated with shallower depths, dense settlements, and increased nutrient input from the land/lakeside. Conversely, the northern areas with intensive fisheries cultivation exhibit a lower trophic response, suggesting that lake depth and hydrodynamics mitigate local nutrient loads. However, without controlling nutrient inputs, these conditions will undoubtedly worsen in the future. Based on the water quality and trophic status of Indonesia's major lakes (Table 4), a similar pattern is observed: waters detected as mildly to moderately polluted are already experiencing "eutrophication", driven by increasing anthropogenic pressures. In this regard, Lake Toba appears to be "better" compared to other priority lakes in Indonesia. However, this condition signals an increase in nutrient levels over the past decade.

Observations from the perspective of water quality and trophic status in Lake Toba actually indicate a relevant relationship between mildly to moderately polluted water quality (class II) and a trophic status that tends toward mesotrophic. Lake Toba's mesotrophic status indicates nutrient accumulation in the lake's waters, where long water residence times and thermal stratification can dampen short-term chemical fluctuations while allowing for gradual nutrient enrichment. Therefore, trophic indices can serve as early warning indicators of ecosystem degradation compared to parameter-based water quality assessments, which are less expensive.

Nationally, Lake Toba's condition is considered "safer" compared to other priority lakes, such as Lake Maninjau, Limboto, and Sentani, which have reached eutrophic to hypereutrophic states accompanied by moderate to severe pollution levels (Table 4). In these systems, ongoing nutrient loads from aquaculture intensification, watershed runoff, and urban waste have exceeded the ecosystem's assimilation capacity, resulting in persistent algal blooms, oxygen depletion, and decreased ecological resilience [37]. In contrast, Lake Toba's current large volume, depth, and hydrodynamic complexity provide a buffering capacity that slows nutrient enrichment.

Table 4. Water quality and trophic status of Lake Toba and priority lakes in Indonesia. This table displays the history of the water quality status and fertility status of Lake Toba based on existing data (2009-2025) as well as a comparison with other priority lakes in Indonesia.

No	Lake	Water quality status	Trophic status	Description
1	Toba (2009)	-	Oligotrophic [46]	TSI method
2	Toba (2018)	Lightly to moderately polluted [18]	Meso-eutrophic [18]	TSI method
3	Toba (2021)	-	Mesotrophic [19]	TSI method
4	Toba (2024)	-	Mesotrophic [10]	Plankton abundance
5	Toba (2024)	Good to Lightly polluted	Mesotrophic	This research (Class II)
6	Toba (2024)	Lightly to moderately polluted	Mesotrophic	This research (Class I)
7	Maninjau	Good to moderately polluted	Hypereutrof [37]	Class I [36]
	Maninjau	Lightly to Moderately polluted		Class II [36]
8	Singkarak	Moderately polluted	Eutrophic [40]	
9	Matano & Towuti	-	Oligotrophic [61]	Satellite imagery
10	Limboto	Moderately polluted [62]	Eutrophic [62]	
11	Poso, Central Sulawesi	Good to Lightly polluted[38]	Mesotrophic [38,63]	TSI method
12	Ayamaru, Papua		Mesotrophic	TSI method[64]
13	Sentani	Moderately to heavy polluted	Eutrophic-hypereutrophic	CCME-WQI and TSI method [42]
14	Rawa pening	Slight pollution [65]	Eutrophic [66]	Stored method and TSI
15	Batur	Slight pollution [67]	Mesotrophic	TSI method [68]

Management Implications for Lake Toba

Lake Toba is a tectonic volcanic lake located in North Sumatra Province, Indonesia. Geographically, it is surrounded by seven regencies and twenty-eight districts [69]. The scenic beauty of the Lake Toba Geopark area has attracted both domestic and international tourists, particularly following its designation as a National Tourism Strategic Area or National Tourism Development Area by the Government of Indonesia [8]. Consequently, the Lake Toba region experienced rapid development, including residential areas, hotels, and restaurants. Additionally, aquaculture and water transportation, particularly to support tourism, have expanded within the lakes, inevitably generating waste that may pollute Lake Toba. The absence of domestic wastewater treatment facilities further accelerates lake pollution. Moreover, agricultural activities around the Lake Toba area contribute to potential waste input, as runoff from the surrounding lands carries pollutants into the lake through its tributary rivers.

Our findings indicate that Lake Toba experienced a decline in water quality and an increase in nutrients, suggesting that its waters are polluted due to elevated nutrient levels and coliform bacterial contamination. Previous studies have reported that the trophic status of Lake Toba remains generally oligotrophic [46–48]. However, this study revealed that the lake status has shifted, with the average classification falling within the mesotrophic category. Similar findings have been reported at various locations, indicating that Lake Toba has experienced an increase in productivity under mesotrophic conditions [18,19,70].

Although this status remained within the mesotrophic (moderate) category, the observed upward trend should serve as a warning for both the public and the government. Greater attention should be given to the development of tourism destinations, particularly the construction of hotels and restaurants, the regulation of floating net cage aquaculture by both communities and corporations, as well as the management of agricultural land within the lake's catchment area. Future research incorporating vertical profiling, long-term monitoring, and nutrient budget analysis is essential to clarify the internal and external loading dynamics. The spatiotemporal baseline generated in this study provides a strong scientific foundation for the adaptive long-term management of Lake Toba and other priority lakes in Indonesia

Conclusions

This study comprehensively assessed the spatial and temporal variations in water quality and trophic status in Lake Toba using integrated water quality indices (PI and CCME-WQI) and trophic state indicators (TSI and TSIlamp). The results indicate that Lake Toba generally complies with Class II water quality standards for fisheries, tourism, and agricultural uses, but does not consistently meet Class I criteria for drinking water sources, primarily because of *Fecal coliform* contamination. The PI classified the lake as lightly polluted under Class I (average 3.53 ± 0.82 during the dry season and 3.44 ± 0.81 during the rainy season) and good to lightly polluted under Class II standards (average 1.72 ± 0.59 during the dry season and 1.74 ± 0.78 during the rainy season). The CCME-WQI results further confirmed generally good water quality conditions, with slightly improved scores during the rainy season.

The trophic status ranged from oligotrophic to eutrophic across the stations, with an overall mesotrophic classification. The increase in the mean trophic index from 42.37 ± 3.43 (dry season) to 47.03 ± 3.98 (rainy season) indicates a gradual rise in ecosystem productivity. Although the lake remains within the mesotrophic category, the seasonal upward trend suggests increasing nutrient pressure and a potential progression toward higher trophic states. These findings highlight the importance of proactive and preventive management, particularly the regulation of floating net-cage aquaculture expansion and the strengthening of nutrient control measures within the catchment. The integrated spatial–temporal framework applied in this study provides a robust scientific basis for long-term monitoring and sustainable management of Lake Toba and other priority lakes in Indonesia

Author Contributions

AM: Conceptualization, Methodology, Investigation, Writing - Review & Editing; **RL**: Investigation, Writing - Review & Editing, Supervision; **AR**: Conceptualization, Methodology; **PRT**: Writing - Review & Editing; **NR**: Investigation, Writing - Review & Editing; **MF**: Mapping, Writing - Review & Editing; **IST**: Mapping, Writing - Review & Editing; and **HH**: Mapping, Writing - Review & Editing.

AI Writing Statement

During the preparation of this work, the authors used ChatGPT to assist with language editing, including correcting grammar and paraphrasing sentences for clarity and precision. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication

Conflicts of interest

There are no conflicts to declare.

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